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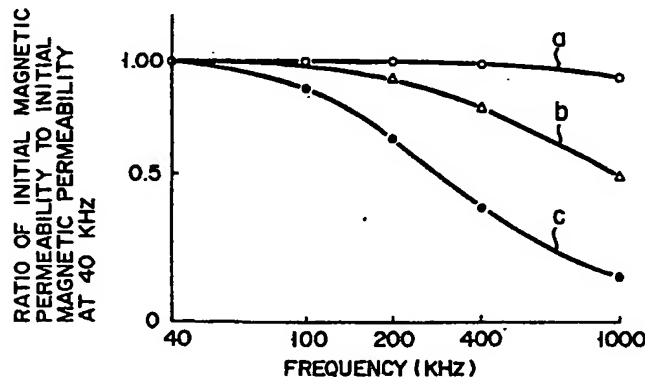
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(54) Compressed magnetic powder core.

(57) A compressed magnetic powder core comprising a compressed body of a magnetic powder and electrically insulating material separating the magnetic powder particles, characterized in that the magnetic powder has an average particle size of 10 to 300  $\mu\text{m}$ , and the insulating material covers each of the particles of said magnetic powder and comprises a continuous insulating film having a thickness of 10  $\mu\text{m}$  or less and comprising a metal alkoxide or a decomposition product thereof.



EP 0 434 669 A2

## COMPRESSED MAGNETIC POWDER CORE

The present invention relates to a compressed magnetic powder core and, more particularly, to a powder core having a high magnetic flux density and good frequency characteristics of magnetic permeability.

Semiconductor switching elements (e.g., thyristors and transistors), turn-on stress buffer reactors, commutating reactors, energy storage reactors or matching transformers have been used as conventional electrical elements in power transformers (e.g., AC/DC converters, DC/DC converters such as choppers, and AC/AC frequency converters) or in electrical equipment such as noncontact switches.

Such conventional reactors and voltage transformers require an iron core having good magnetic characteristics in a high-frequency range.

Currents having switching frequencies of either several tens of Hz to 200 kHz or several tens of kHz or 500 kHz or more, often flow in conventional reactors and voltage transformers. Therefore, demand has arisen for an iron core which has a low iron loss and whose magnetic permeability is not reduced in a high-frequency range.

An eddy current loss among iron loss components in AC excitation of an iron core increases proportionally to the square of frequency when a magnetic flux density remains the same. Most of the iron loss is accounted for by the eddy current loss in the high-frequency range. As a result, the iron loss is increased and the magnetic permeability is decreased in the high-frequency range.

In a conventional iron core made of a metallic magnetic powder, a decrease in iron loss is achieved by improvement of electrical insulation between the magnetic particles.

Typical conventional iron cores having good high-frequency characteristics are exemplified by so-called dust cores as described in Japanese Patent Nos. 88779 and 112235.

Although such dust cores have good high-frequency characteristics, their magnetic flux density is low. For example, a maximum magnetic flux density at a magnetizing force of 10000 A/m is only 0.125 T.

In another conventional iron core having metallic magnetic powder and a binder resin as disclosed in Japanese Patent No. 670518, good frequency characteristics and a high magnetic flux density can be obtained.

We acknowledge the disclosure in Japanese Patent Application No. 55-138205 of a compressed magnetic dust core comprising an iron powder mixed with an insulating powder of mica, montmorillonite graphite, molybdenum dioxide or boron nitride, together with a bonding agent such as organic resin; gaps between the iron particles are filled by the insulating powder and the bonding agent.

We also acknowledge that British patent No. 736,844 disclosed the annealing of a magnetic dust core in which magnetic alloy powder is pre-mixed with colloidal silica which is thereby deposited between the magnetic alloy particles.

Generally, in the iron core manufactured by compression molding a metallic magnetic powder, magnetostriction caused by compression increases a coercive force as compared with that prior to compression. In addition, a hysteresis loss is increased accordingly. In order to obtain a low-loss iron core, magnetostriction must be eliminated. For this purpose a heat treatment (annealing) is normally performed to effectively eliminate such magnetostriction. In the iron core having the binder resin, however, the resin is decomposed or degraded during the heat treatment, and electrical insulation between the metal magnetic particles cannot be guaranteed. It is thus difficult to manufacture an iron core having a low iron loss.

It is, therefore, an object of the present invention to provide a compressed magnetic powder core which has a high magnetic flux density, good frequency characteristics of magnetic permeability, and a low hysteresis loss due to annealing.

Accordingly, the present invention provides a compressed magnetic powder core as defined in Claim 1.

This Application has been divided from European Application No. 85306848, EP-A-0177276.

This invention can be more fully understood from the following detailed description of specific examples when taken in conjunction with the accompanying drawing showing the initial frequency characteristics of the permeability of a core embodying the present invention and those of comparative examples.

A compressed magnetic powder core embodying the present invention is obtained by compressing a metallic magnetic powder, each particle of which is covered with an insulating layer of a specific insulating material. The metallic magnetic powder used in the present example is preferably an iron-based magnetic powder such as pure iron, an iron-silicon alloy (e.g., Fe-3% Si) powder, an iron-aluminum alloy powder, an iron-nickel alloy powder, an iron-cobalt alloy powder, or an iron-containing amorphous alloy (e.g., an alloy containing iron and at least one of silicon, boron and carbon as a major component). One or a mixture of at least two of these magnetic powders can be used.

These metallic magnetic powders have a resistivity of  $10\mu\Omega$  cm to several tens of  $\mu\Omega$  cm. In order to obtain good core material properties for an AC current including one of high frequency giving rise to the skin effect, the magnetic powder must consist of micro-particles so as to sufficiently be magnetized from surfaces to centers thereof.

5 For example, in a magnetic powder core which is to be excited by a current having a frequency component of several tens of kHz and which must have satisfactory permeability characteristics up to this frequency component, an average particle size is preferably  $300\mu\text{m}$  or less.

In a magnetic powder core to be excited in a frequency range of 100 kHz or more, an average particle size is preferably  $100\mu\text{m}$  or less.

10 When the average particle size of the magnetic powder is smaller than  $10\mu\text{m}$ , a satisfactory density of the core cannot be obtained at a normal pressure of 1,000 MPa or less. As a result, the magnetic flux density is low. The average particle size is preferably  $10\mu\text{m}$  or more.

The magnetic powder can be used as it is or after a natural oxide layer of several tens of nm which is formed on the surface of each particle in air is reduced. This reduction is performed by heating the powder 15 in, for example, a hydrogen atmosphere.

Each particle of the magnetic powder used in the present invention is covered with an insulating layer of a specific insulating material. The insulating material is a metal alkoxide or a decomposition product of the metal alkoxide.

The particles of the magnetic powder can be properly insulated by using a metal alkoxide with the 20 following general formula:



wherein M is a metal or semi-metal atom, R is an alkyl group, and x is a valence of M.

25 Almost all metal or semi-metal elements in the Periodic Table constitute metal alkoxides. However, the metal element M used for a metal alkoxide in the present invention should not comprise a radioactive element.

In the above formula, the alkyl group must have at least one carbon atom but can generally have 1 to 5 carbon atoms as exemplified by a methyl group, ethyl group, propyl group, butyl group or pentyl group.

30 The metal alkoxide in the general formula described above includes, for example,  $\text{Si}(\text{OCH}_3)_4$ ,  $\text{Ti}(\text{OC}_2\text{H}_5)_4$ ,  $\text{In}(\text{OC}_3\text{H}_7)_3$ ,  $\text{Al}(\text{OC}_4\text{H}_9)_3$ ,  $\text{Zr}(\text{OC}_5\text{H}_{11})_4$  or  $\text{Ta}(\text{OC}_3\text{H}_7)_5$ . Any one of these alkoxides or a mixture of two or more of them may be used.

This metal alkoxide is brought into contact with the metallic magnetic powder, and the metal alkoxide or its decomposition product (e.g., an oxide, hydroxide or hydrate) is formed as a layer on the surface of the 35 metallic magnetic powder.

The metal alkoxide is brought into contact with the metallic magnetic powder to form the deposited layer in the following manner:

(1) The magnetic powder is dipped and stirred in a solution of a metal alkoxide in an organic solvent. The organic solvent is filtered out or evaporated to provide the magnetic powder;

40 (2) After solution of a metal alkoxide in an organic solvent is sprayed onto the metallic magnetic powder, the powder is dried; or

(3) A vapor of a metal alkoxide is brought into contact with the magnetic powder.

The resultant deposited layer comprises the metal alkoxide itself or an oxide or hydroxide produced by decomposition of the metal alkoxide. In general, the metal alkoxide is hydrolysed by moisture adsorbed on 45 the surface of the metallic magnetic powder to form a deposited layer of a metal oxide ( $\text{MO}_{x/2}$ ) or metal hydroxide ( $\text{M(OH)}_x$ ). Alternatively, the deposited layer may comprise a hydrate. Furthermore, a metal alkoxide and a hydroxide of the deposited layer may be oxidized by heating into an oxide. The decomposition products (without heating) of the insulating deposition layer are listed in Table A below:

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Table A

| Element | Decomposition Product   | Element | Decomposition Product               |
|---------|-------------------------|---------|-------------------------------------|
| Li      | LiOH                    | Cd      | $\text{Cd(OH)}_2$                   |
| Na      | NaOH                    | Al      | AlOOH                               |
| K       | KOH                     |         | $\text{Al(OH)}_3$                   |
| Be      | $\text{Be(OH)}_2$       | Ga      | GaOOH                               |
| Mg      | $\text{Mg(OH)}_2$       |         | $\text{Ga(OH)}_3$                   |
| Ca      | $\text{Ca(OH)}_2$       | In      | $\text{In(OH)}_3$                   |
| Sr      | $\text{Sr(OH)}_2$       | Si      | $\text{Si(OH)}_4$                   |
| Ba      | $\text{Ba(OH)}_2$       | Ge      | $\text{GeO}_2$                      |
| Ti      | $\text{TiO}_2$          | Sn      | $\text{Sn(OH)}_4$                   |
| Zr      | $\text{ZrO}_2$          | Pb      | $\text{PbO } 1/3\text{H}_2\text{O}$ |
| Nb      | $\text{Nb(OH)}_5$       |         | PbO                                 |
| Ta      | $\text{Ta(OH)}_5$       | As      | $\text{As}_2\text{O}_3$             |
| Mn      | MnOOH                   | Sb      | $\text{Sb}_2\text{O}_5$             |
|         | $\text{Mn(OH)}_2$       | Bi      | $\text{Bi}_2\text{O}_3$             |
|         | $\text{Mn}_3\text{O}_4$ | Te      | $\text{TeO}_2$                      |
| Fe      | FeOOH                   | Y       | YOOH                                |
|         | $\text{Fe(OH)}_2$       |         | $\text{Y(OH)}_3$                    |
|         | $\text{Fe(OH)}_3$       | La      | $\text{La(OH)}_3$                   |
|         | $\text{Fe}_3\text{O}_4$ | Nd      | $\text{Nd(OH)}_3$                   |
| Co      | $\text{Co(OH)}_2$       | Sm      | $\text{Sm(OH)}_3$                   |
| Cu      | CuO                     | Eu      | $\text{Eu(OH)}_3$                   |
| Zn      | ZnO                     | Gd      | $\text{Gd(OH)}_3$                   |

The insulating layer of metal alkoxide and/or its decomposition product constitutes a continuous film on the surface of each particle of the magnetic powder.

The thickness of the insulating layer is sufficiently 10  $\mu\text{m}$  or less.

As described above, the magnetic powder having the insulating layer thereon is filled in molds and is compression molded at a pressure of 1,000 MPa or less which can be easily, commercially achieved,

thereby obtaining a magnetic core of a desired shape. In order to lower magnetostriction of the core caused by pressure during compression molding, a heat treatment at a temperature of 450 °C to 1,000 °C for 0.5 hour or more is available. In the conventional technique using an interparticle insulating resin, when the heat treatment is performed to lower magnetostriction, the resin is decomposed and degrades its electrical insulation property. According to the present invention, however, such a problem does not occur. With the heat treatment, the coercive force and hysteresis loss can be decreased without degrading the electrical insulation property, thereby decreasing the iron loss.

The present invention will be described in detail by way of examples.

Examples 1 to 7, and Comparative Examples 1 to 5, are set out in the parent Application EP-A-0177276, and need not be repeated here as they are outside the scope of the present invention.

#### Examples 8 and 9

An Fe-1.5% Si alloy powder (100 grams) having an average particle size of 54  $\mu\text{m}$  in Example 8 and an Fe-1.5 Si alloy powder (100 grams) having an average particle size of 105  $\mu\text{m}$  in Example 9 were each dipped and stirred in a 15% butyl acetate solution (200 ml) of  $\text{Zr}(\text{OC}_4\text{H}_9)_4$ . The butyl acetate solution was filtered out, and the resultant alloy powders were dried at a temperature of 20 °C for 2 hours. 20 grams of each of the resultant magnetic powders were respectively filled in molds and were molded at a pressure of 800 MPa, thereby preparing magnetic cores.

#### Example 10

An Fe-3% Al alloy powder (100 grams) having an average particle size of 69  $\mu\text{m}$  was exposed to a  $\text{Ti}(\text{OC}_3\text{H}_7)_4$  vapor. In this case, the vapor concentration of  $\text{Ti}(\text{OC}_3\text{H}_7)_4$  was 2,000 ppm at a temperature of 200 °C. 20 grams of the resultant magnetic powder was used to prepare a core in the same manner as in Examples 8 and 9.

#### Comparative Example 6 and 7

An Fe-1.5% Si alloy powder (20 grams) having an average particle size of 54  $\mu\text{m}$  in Comparative Example 6 and an Fe-3% Al alloy powder (20 grams) having an average particle size of 69  $\mu\text{m}$  in Comparative Example 7 were respectively filled in the molds and were molded at a pressure of 800 MPa to prepare magnetic cores.

The above cores had a high magnetic flux density of 0.8 T or more at a magnetizing force of 10,000 A/m. The frequency characteristics of the initial magnetic permeabilities of these cores were measured. Results are shown in the accompanying drawing, in which initial magnetic permeability ratios are represented by the initial magnetic permeability at 40 KHz given as 1. Curve a represents the initial permeability ratio in Example 8; b, in Example 9; and c, Comparative Example 6. As is apparent from the drawing, the initial magnetic permeability of the core of Example 8 was not substantially degraded up to 1 MHz, and the initial magnetic permeability of the core of Example 10 was not substantially degraded up to 200 KHz. However, the initial magnetic permeability of the core of Comparative Example 6 was greatly degraded starting from 100 KHz. The frequency characteristics of the core of Example 10 were substantially the same as those of Example 8. The initial magnetic permeability of the core of Comparative Example 7 was greatly degraded.

The core of Example 8 was heat treated in an Ar atmosphere at a temperature of 500 °C for 2 hours. The coercive force of the core prior to the heat treatment was 480 A/m, but was decreased to 280 A/m after the heat treatment. Therefore, the iron loss in the high-frequency range was decreased to less than 65%.

In the compressed magnetic powder core according to the present invention as described above, since the surface of each particle of the magnetic powder constituting the powder core is effectively covered with an insulating layer of a metal alkoxide, or its decomposition product, a high magnetic density can be provided and at the same time the eddy current loss can be decreased, thereby achieving a high magnetic permeability up to a high-frequency range. In addition, the core of the present invention can be heat treated at a high temperature, and the hysteresis loss can be decreased. As a result, the iron loss can be decreased.

#### Claims

1. A compressed magnetic powder core comprising a compressed body of a magnetic powder and

electrically insulating material separating the magnetic powder particles, characterized in that the magnetic powder has an average particle size of 10 to 300  $\mu\text{m}$ , and the insulating material covers each of the particles of said magnetic powder and comprises a continuous insulating film having a thickness of 10  $\mu\text{m}$  or less and comprising a metal alkoxide or a decomposition product thereof.

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2. A core according to Claim 1, characterized in that the magnetic powder comprises an iron-based magnetic material.

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3. A core according to Claim 1 or 2, characterized in that the decomposition product includes a metal oxide and/or a metal hydroxide.

4. A core according to claim 1, 2 or 3, characterized in that the metal alkoxide has an alkyl group having 1 to 5 carbon atoms.

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5. A core according to claim 4, characterized in that the metal alkoxide is selected from the group consisting of alkoxides of lithium, sodium, potassium, beryllium, magnesium, calcium, strontium, barium, titanium, zirconium, niobium, tantalum, manganese, iron, cobalt, copper, zinc, cadmium, aluminum, gallium, indium, silicon, germanium, tin, lead, arsenic, bismuth, tellurium, yttrium, lanthanum, neodymium, samarium, europium and gadolinium, and a mixture thereof.

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